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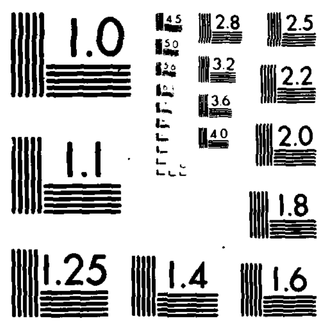

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A simple scheme is proposed for the construction of a wide-band fast wave gyrotron travelling wave amplifier. The key features of this scheme include a contoured waveguide, a tapered magnetic field, and injection of input signals in opposite direction of the streaming electrons. Bandwidths at tens of percents, and gain at tens of decibels, are projected.

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CONTENTS

ON A WIDE-BAND FAST WAVE GYROTRON TRAVELLING WAVE AMPLIFIER

I. INTRODUCTION

Current experiments[1,2] on the gyrotron travelling wave amplifier (Gyro-TWA) are operated with the fast wave branch of the cyclotron maser instability. The bandwidth achieved in experiments is on the order of a few percent. This rather low bandwidth is believed to be due to the following limitations: (a) The near cutoff operating condition that limits the accessibility of waves of lower frequencies and (b) the effect of the velocity spread which deteriorates the gain of waves at higher frequencies.[2,3] While the recently proposed slow wave cyclotron amplifier[4] predicts a much wider bandwidth, the velocity spread may still be a severe limitation.

Thus, to achieve a bandwidth on the order of tens of percent, the obstacles mentioned in the previous paragraph must be eliminated. It is recognized that, in principle, a variable cross section in the waveguide, together with a tapered magnetic field, may increase the bandwidth. However, a moment of reflection would lead to the inevitable conclusion that waves with frequencies lower than the cut-off frequency of the narrowest region cannot be amplified for they cannot enter the waveguide. The success in the utilization of such concepts then hinges on the accessibility of the low frequency waves.

In this paper, we propose a wide-band, efficient, gyro-TWA operated with the fast wave branch. This scheme relies on elementary concepts and, therefore, has the advantage of being simple. The difficulties discussed above are largely removed. The key features of this scheme include a tapered magnetic field, a waveguide with a variable cross section, and injection of input signals in opposite direction of the streaming electrons. The disadvantage of the cutoff frequency is turned into our advantage to admit amplification of low frequency waves. Thus, achieving bandwidths and efficiency at tens of percents is a distinct possibility.

Manuscript submitted September 30, 1980.

In Section II, we describe the scheme of such a wide-band amplifier. This scheme may be regarded as a specific example of the more general concept of distributed amplification.[5] The linear gain and bandwidth are calculated. Included also is an example which may be used in a "proof of principle" experiment. In this example, bandwidth on the order of 14%, and gain on the order of 40 dB are projected. In the final section, we discuss certain issues related to this scheme. Other schemes, as well as calculations on nonlinear gain and bandwidths are presented in a separate publication.[(5)]

II. THE PROPOSED SCHEME

In this section, we outline the details of the scheme for the proposed wide-band gyro-TWA. In subsection (A). The concepts are described. In subsection (B), we calculate the gain, bandwidth, and other quantities of interest in a model utilizing these concepts. In subsection (C), a specific example is suggested for use in a "proof of principle" experiment.

A. Conceptual Design

Consider a circular waveguide of variable cross section as shown in Fig. 1. Let the relativistic electron beam be injected from the narrow region and be drifting in the positive z direction. Denote r_1 and r_2 to be the radius of waveguide at the two ends. Let $r_2 > r_1$, as shown in Fig. 1. Adjust the magnetic field so that it assumes a grazing value [Fig. 2] locally everywhere along the waveguide. Inject the input signal of frequency ω from the downstream of the electron beam (Fig. 1). Suppose that

$$\omega_2 < \omega < \omega_1 \tag{2}$$

where ω_1 (ω_2) is the cutoff frequency of a uniform waveguide of radius r_1 (r_2). That is,

$$\omega_{1,2} = c\zeta_{on}/r_{1,2} \tag{3}$$

with c being the speed of light and ζ_{on} is the n^{th} nontrivial zero of J_1, the Bessel function of order one.

The injected signal will first propagate upstream of the electron beam, but hardly interacts with it. This left-ward propagating wave will then be reflected by the constriction of the waveguide. This reflected wave propagates to the right. While comoving with the beam, it always experiences a grazing magnetic field, [Fig. 2] and is thus subject to strong amplification. From this simple concept, it is easily seen that the bandwidth may be as high as $2(r_2 - r_1)/(r_2 + r_1)$, which is arbitrary since r_1, r_2 are yet unspecified. Note that this wide-band amplifier is not degraded by the velocity spread, since the amplifier is always operated at the grazing condition, at which k_z is small.* Thus, the difficulties mentioned at the beginning of this paper are avoided in such an amplifier. The gain of this amplifier, of course, depends on the axial length of the waveguide. [c.f. Eq. (21) below].

B. Calculations

To provide a quantitative evaluation, the geometry of the waveguide needs to be specified. Therefore, for simplicity, consider a waveguide whose wall radius $r_w(z)$ is as shown in Fig. (3). The annular electron beam of beam radius r_{00} is injected at $z = 0$. We take

$$r_w(z) = \begin{cases} r_1, & 0 < z < z_1 \\ r_1 + \dfrac{(r_2 - r_1)}{(z_2 - z_1)}(z - z_1) & z_1 < z < z_2 \\ r_2, & z > z_2. \end{cases} \tag{4}$$

In practice, the sharp corners at z_1 and z_2 of the wall radius may be avoided. Our calculation is not affected by such smooth connections if we are only interested in obtaining a virtually flat gain curve over a more restricted frequency range

$$\omega_l < \omega < \omega_u \tag{5}$$

where

$$\omega_{l,u} = \zeta_{on}\, c/r_{l,u} \tag{6}$$

with $r_1 < r_u < r_l < r_2$ [cf. Fig. (3)]. We further assume

$$\omega_u = 0.85\, \omega_1 \tag{7}$$

and

$$\omega_l = \frac{1}{0.85}\, \omega_2 \tag{8}$$

where ω_u (ω_l) signifies the upper (lower) bounds of the frequency band. The choice of ω_u to be less than ω_1 (cf. Eq. (7)) is required so that the incoming signal would be totally reflected coherently. The

*Recall that the effect of velocity spread $\langle \Delta p_z \rangle$ enters in the combination $(k_z \langle \Delta p_z \rangle)^2$ qualitatively. See, e.g., Ref. (6).

choice of ω_l to be greater than ω_2 (cf. Eq. (8)) is required so that the wave with frequency ω_l would experience total amplification before it leaves the point $z = z_2$. A dividend of the choice $\omega_l < \omega_2$ is that this exiting wave would also suffer very little scattering as it reaches the corner z_2, as ω_l is considerably higher than the cutoff frequency ω_2. Another advantage is that the couplings of input and of output might be made easier if z_l is sufficiently far away from z_2.

We shall now calculate the gain of a signal of frequency ω. In view of (5), this signal will be reflected at $z = z_t$, where $z_t = z_t(\omega)$ is defined by

$$\omega = \zeta_{on}\, c/r_w(z_t) \equiv \zeta_{on}\, c/r_t(\omega), \tag{9}$$

$$r_t(\omega) \equiv \zeta_{on}\, c/\omega. \tag{10}$$

From the WKBJ theory, the gain $G(\omega)$ is given by

$$G(\omega) = \int_{z_t(\omega)}^{z_2} dz\; k_i\,(\omega;z) \tag{11}$$

where $k_i(\omega;z)$ is the local amplification rate per unit length, to be obtained from the local dispersion relationship. We shall now show that $G(\omega)$ can be made to be a constant for all ω between ω_l and ω_u.

First, we record that the normalized local dispersion relationship for the gyro-TWA is given by[6]

$$(\bar{k}^2 + 1 - \bar{\omega}^2)\,(\bar{k}\beta_{||} + b_o - \bar{\omega})^2 = \epsilon \tag{12}$$

where

$$\bar{\omega} \equiv \omega/\omega_c\,(z) = \omega\; r_w(z)/\zeta_{on}c \tag{13}$$

$$\bar{k} \equiv k_z r_w(z)/\zeta_{on} \tag{14}$$

$$\beta_{11} \equiv v_{oz}\,(z)/c \tag{15}$$

$$b_o \equiv \sqrt{1-\beta_{||}^2} \tag{16}$$

$$\epsilon \equiv \frac{4\nu\; v_{\perp 0}^2 H_{sm}\left(\frac{r_o}{r_w},\, \frac{r_L}{r_w}\right)}{\gamma_0\, \zeta_{on}^2\, J_o^2\,(\zeta_{on})\, c^2}. \tag{17}$$

Here, k_z is the local (complex) wave number, v_{oz} is the local axial velocity of the electron, $\nu = Ne^2/mc^2$ with N being the number of electrons per unit length, $v_{\perp 0}$ is the velocity of electron transverse to the magnetic field, J_p is the Bessel function of order p, $r_L = v_\perp/\Omega_c$ is the local electron

Larmor radius, r_o is the local beam position and $H_s(\chi, y) = [J_s(\chi)\ J'_s(y)]^2$ for the s-th cyclotron harmonics. If $r_2/r_1 \lesssim 2$, and if $r_{oo}/r_1 \approx 0.75$, it may be shown that ϵ can be made an approximate constant. Let us further assume that $\beta_{||}$ is also approximately a constant, then $G(\omega)$ can be calculated easily from the published gain curves for a *uniform* waveguide.[3]

The solution to (12) yields the normalized amplification rate

$$\bar{k}_i = \bar{k}_i\ (\bar{\omega}) \tag{18}$$

Then Eq. (11) gives

$$\begin{aligned} G(\omega) &= \int_{z_l(\omega)}^{z_2} dz\ \frac{\zeta_{on}}{r_w(z)}\ \bar{k}_i \left[\frac{\omega r_w(z)}{c\zeta_{on}}\right] \\ &= \int_{\bar{\omega}=1}^{\bar{\omega}=\omega/\omega_2} d\bar{\omega} \left[\frac{dz}{d\bar{\omega}}\right] \frac{\zeta_{on}}{r_w(z)}\ \bar{k}_i\ (\bar{\omega}), \\ &= \frac{\zeta_{on}\ (z_l - z_u)}{(r_l - r_u)} \int_{\bar{\omega}=1}^{\bar{\omega}=\omega/\omega_2} \frac{d\bar{\omega}}{\bar{\omega}}\ \bar{k}_i\ (\bar{\omega}). \end{aligned} \tag{19}$$

In writing the last expression, we have used Eq. (13) and Eq. (4).

Extensive data for $\bar{k}_i\ (\bar{\omega})$ as a function of $\bar{\omega}$ have been given in Ref. (3). A typical sketch is shown here in Fig. 4, in which the unstable band extends between $\bar{\omega} = 1$ and $\bar{\omega} = 1 + a$, with a $\lesssim$ 12%. Thus, the last integral in (19) is independent of ω for all ω satisfying Eqs. (5-8). If we further approximate $d\bar{\omega}/\bar{\omega}$ by $d\bar{\omega}$ in (19), we have, to a good approximation,

$$G(\omega) = G = \text{constant},\ \omega_l < \omega < \omega_u \tag{20}$$

where

$$G \equiv \frac{\zeta_{on}\ (z_l - z_u)}{(r_l - r_u)} \times A \tag{21}$$

with A being the area bounded by the curve representing the normalized amplification rate $\bar{k}_i(\bar{\omega})$ as a function of $\bar{\omega}$. From (20), (6), and Fig. (5) it is clear that the bandwidth (BW) is given by

$$BW = \frac{2\ (r_l - r_u)}{r_l + r_u}. \tag{22}$$

The gain-bandwidth product is then approximately constant whose value is proportional to the length of the system, inversely proportional to the mean radius of the waveguide, but is otherwise independent of the difference in radius.

We shall now show that a reflected signal in a geometry such as that shown in Fig. (3) is a coherent one. This can be done by showing (1) that there is a definite phase relationship between the incident and reflected wave and (2) that the amplitude at $z = 0$ is extremely small so that any incoherence introduced by secondary reflections at $z = 0$ can be neglected.

To this end, the well-known WKBJ technique suffices as it has been demonstrated to be extremely accurate in these "turning point" problems. The propagation of waves in an irregular waveguide such as that shown in Fig. 3 is given by

$$\frac{d^2u}{dz^2} + k_z^2\,(\omega,z)\;u = 0 \tag{23}$$

where

$$k_z^2\,(\omega,z) \equiv \frac{\omega^2}{c^2} - \frac{\zeta_{on}^2}{c^2\, r_\omega^2(z)}. \tag{24}$$

Note that $k_z\,(\omega,z_t) = 0$, i.e., z_t is a "turning point" of the differential Eq. (23). A uniformly valid solution which is recessive for $z < z_t$ is

$$u = k_z^{-1/2}\,\zeta^{1/2}\,[J_{1/3}\,(\zeta) + J_{-1/3}\,(\zeta)] \tag{25}$$

where

$$\zeta \equiv \int_{z_t}^{z} k_z\, dz \tag{26}$$

and $J_{\pm 1/3}$ is the Bessel function of order $\pm 1/3$. In Eq. (25), the branch k_z in the solution (25) is immaterial since the solution u is an analytic function of z. Asymptotically, Eq. (25) gives

$$u \approx k_z^{-1/2}\sqrt{\frac{6}{\pi}}\cos\left[\int_{z_t}^{z} k_z\, dz - \frac{\pi}{4}\right];\; z >> z_t \tag{27}$$

$$u \approx k_z^{-1/2}\,\frac{1}{2}\sqrt{\frac{6}{\pi}}\exp\,[-\int_{z}^{z_t} |k_z|\; d_z]\;;\; z << z_t. \tag{28}$$

Note that the solution (27) consists of an incoming and reflected wave, with a phase shift of $\pi/2$ and that Eq. (28) represents the attenuated wave. From (28) and (27), we derive the following transmission coefficient T at $z = 0$:

$$T \equiv \left|\frac{u\;(\omega,0)}{u\,(\omega,z_2)}\right| \approx \exp\,[-\int_{0}^{z_t} |k_z|\; dz] \tag{29}$$

apart from a multiplying constant of order unity. When we use Eqs. (4) and (24) in (29), we have

$$T = \exp\left[-l_1 - l_2\right] \tag{30}$$

where

$$l_1 = \zeta_{on} \frac{z_1}{r_1} \rho \tag{31}$$

$$l_2 = \zeta_{on} \left[\frac{z_u - z_l}{r_u - r_l}\right] \left[\frac{1}{2} \ln \left[\frac{1+\rho}{1-\rho}\right] - \rho\right] \tag{32}$$

$$\rho \equiv [1 - (\omega/\omega_1)^2]^{1/2}. \tag{33}$$

In (30), the factor l_1 accounts for the attenuation over the distance $0 < z < z_1$ and l_2 for $z_1 < z < z_l$. Typically, $T < e^{-10}$. Thus, virtually no incoherence is introduced due to the minute secondary reflections at $z = 0$. One can demonstrate in a similar fashion that the scattering of waves with $\omega = \omega_u$ at z_2 is also exponentially small.

C. An Example

As an example for the present study let us take $r_1 = 0.5$ cm, $r_2 = 0.8$ cm, $z_1 = 3$ cm, $z_2 - z_1 = 50$ cm, $r_u = .588$ cm, $r_l = 0.68$ cm. Then, the transmission coefficient T is about 3×10^{-22}, and uniform gain may be obtained for $\omega_l < \omega < \omega_u$ with $\omega_l/2\pi = 26.907$ GHz and $\omega_u/2\pi = 31.116$ GHz. The bandwidth is 14.5%. This value of bandwidth is already a factor of ten higher than that achieved in reported experiments to date. If we take $r_{00}/r_1 \approx 0.75$, I = 3 amps, $\beta_{11} = 0.266$, $v_{\perp 0}/v_{0 \parallel} = 1.5$, then for the TE_{01} mode, the gain G over this band would be 4.6 i.e., about 40 dB. The above parameters might be used for testing of the principle.

III. DISCUSSIONS

In this paper, a new scheme for the wideband gyro-TWA is developed utilizing rather simple concepts. The manner is which the waveguide cross section and magnetic field are tapered such as that shown in Fig. 3 turns out also to be an optimum one to achieve maximum efficiency. Even though we have offered only an example with a modest bandwidth of 14% in this paper, we feel that bandwidths as high as 50% might be within reach[5] if the device and its components are carefully designed (see below).

The advantages of the present scheme may now be summarized as follows:

(a) Its bandwidth is theoretically unlimited.

(b) It operates with the fast wave. Thus, structurally it is simpler.

(c) It is not degraded, to a great extent, by the velocity spread.

(d) The gain and efficiency are significant.

(e) Coherence of signal is not destroyed.

(f) Oscillations, if present, may be localized as a result of spatial non-uniformity.

One of the technical problems which needs to be solved for the operation of this amplifier is the coupling (or, decoupling) of the input and output signals, as the latter are located in the same spatial vicinity. Here, the experiments to be performed at Yale University[7] may be of help, and this issue does not seem to be insurmountable.

Another technical difficulty which may ultimately limit the bandwidth is the precise adjustment of the local magnetic field. For in the present scheme, the wide bandwidth depends on identical amplification over its respective amplifying region of each frequency, and it is well-known that the gain is a very sensitive function of the magnetic field. Furthermore, very wide bandwidths require a very long system, in which case the beam quality—in terms of its position, its velocity spread, its value of $v_\perp/v_\parallel$, etc.,—may deteriorate. Even in such an event, wide bandwidths may still be maintained,* but at the expense of the efficiency and gain. Thus, despite these ultimate limitations, it is perhaps not too optimistic to say that linear bandwidths on the order of 10% should be readily achievable with the use of the present scheme.

*Methods such as distributing wall resistivity over certain sections of the wave guide, or lowering the magnetic field over certain sections, may bring the gain $G(\omega)$ uniform over a wide frequency range.

ACKNOWLEDGMENT

We like to thank Drs. L. Barnett and V. L. Granatstein for discussions. This work is supported in part by NAVELEX, Task XF54581007 and ONR, Project No. RR0110941.

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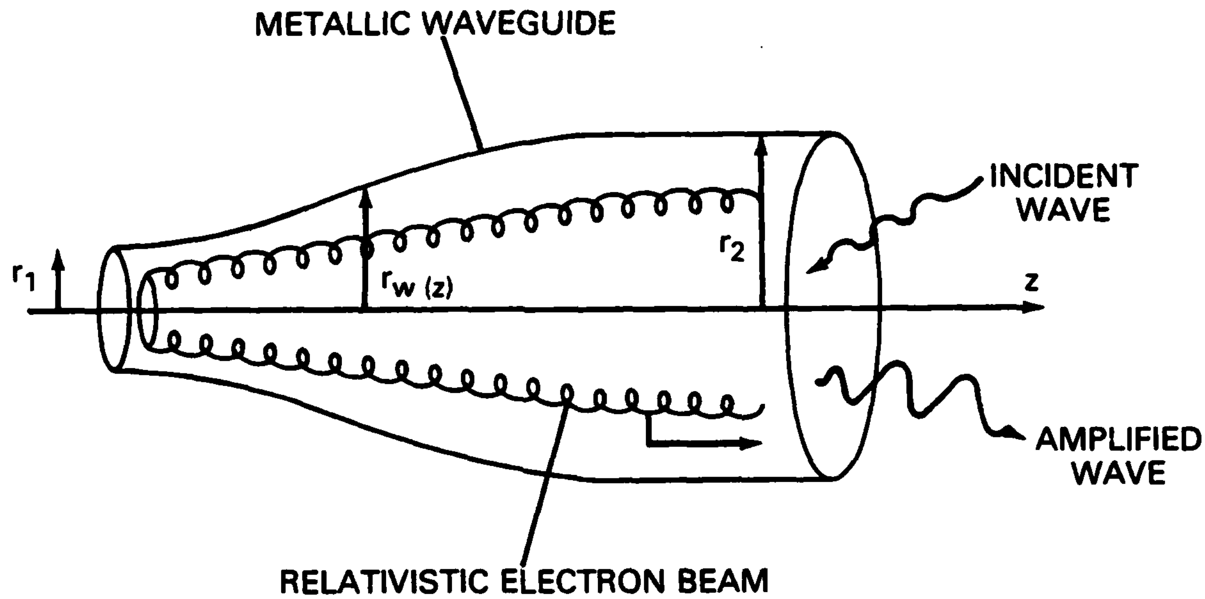

Fig. 1 — Schematic drawing of the proposed wide-band amplifier.

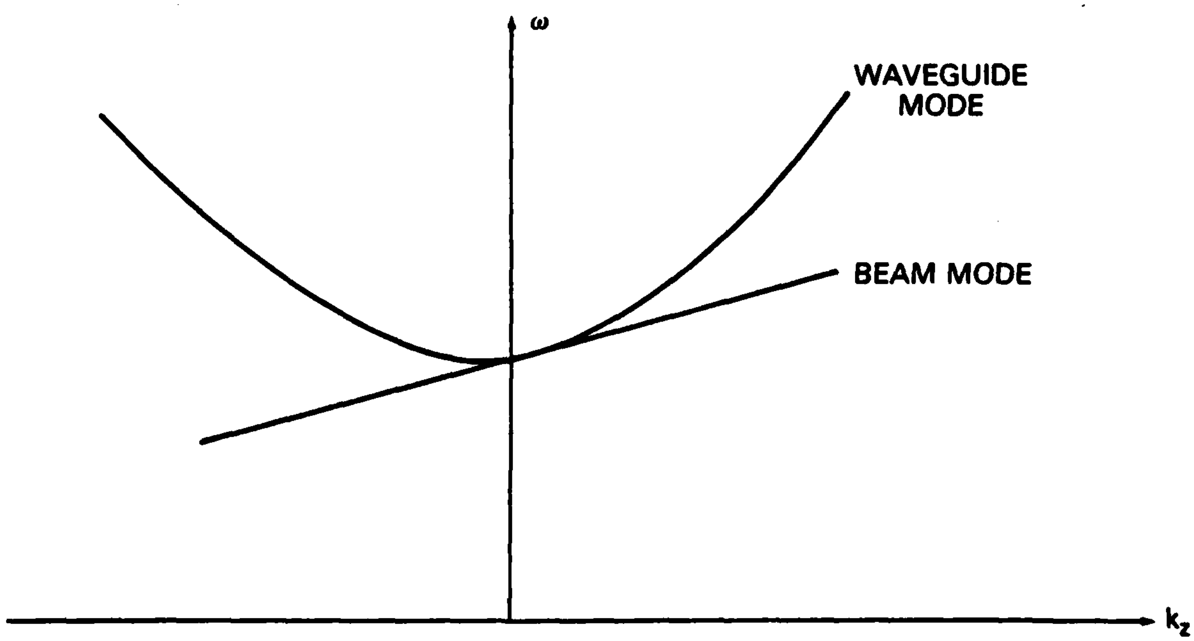

Fig. 2 — The local dispersion relation of the waveguide mode and the beam mode. The local grazing condition is achieved when the two curves are barely touching, for each exial position.

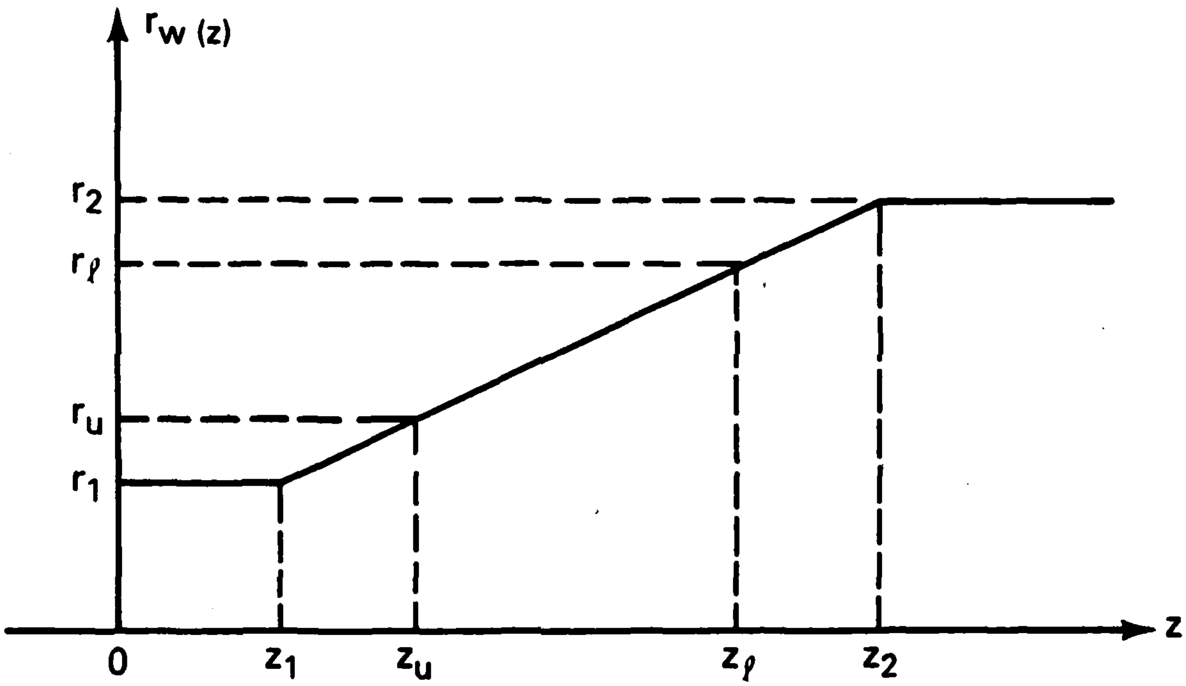

Fig. 3 — The wall radius as a function of axial distance.

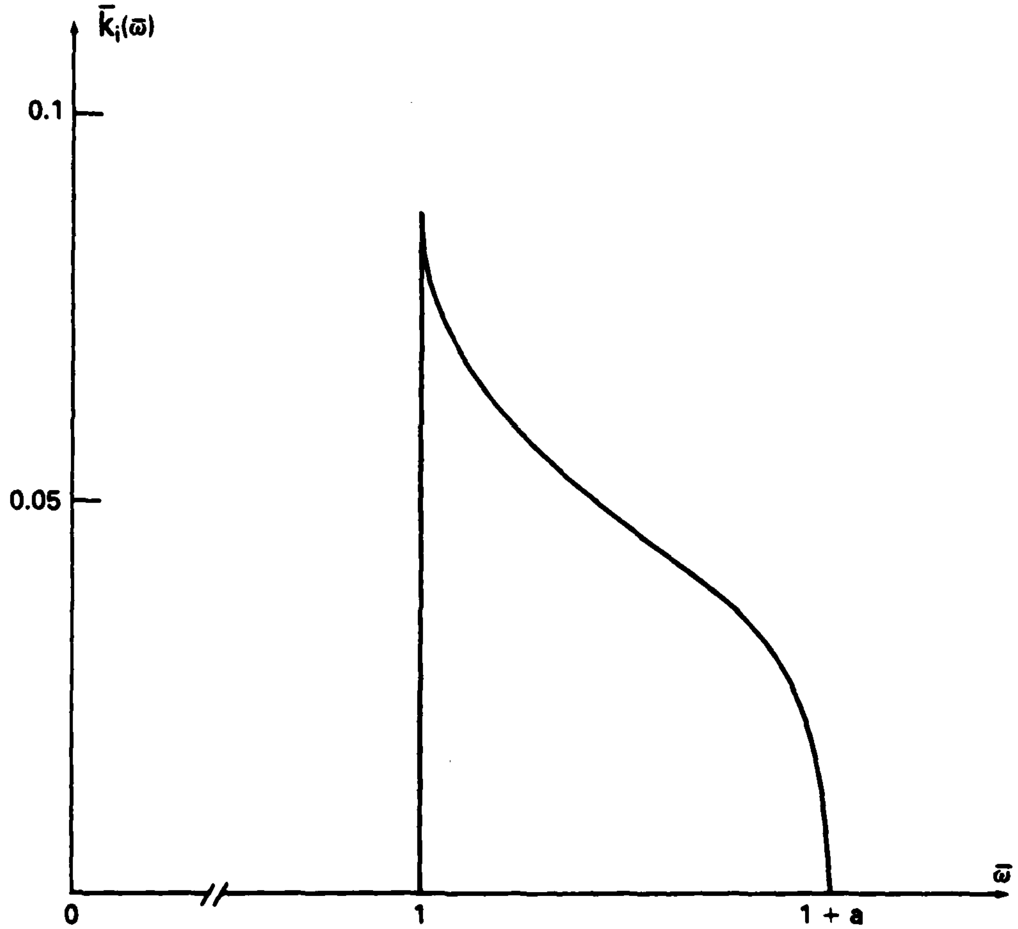

Fig. 4 — The normalized e-folding rate $\bar{k}_i$ as a function of the normalized frequency $\bar{\omega}$. The data is obtained for $I = 3$ amps, $v_{\perp}/v_{\parallel 0} = 1.5$, $\beta_{\parallel 0} = 0.266$, and axial velocity spread of 7%. In this graph, $a \approx 0.12$.

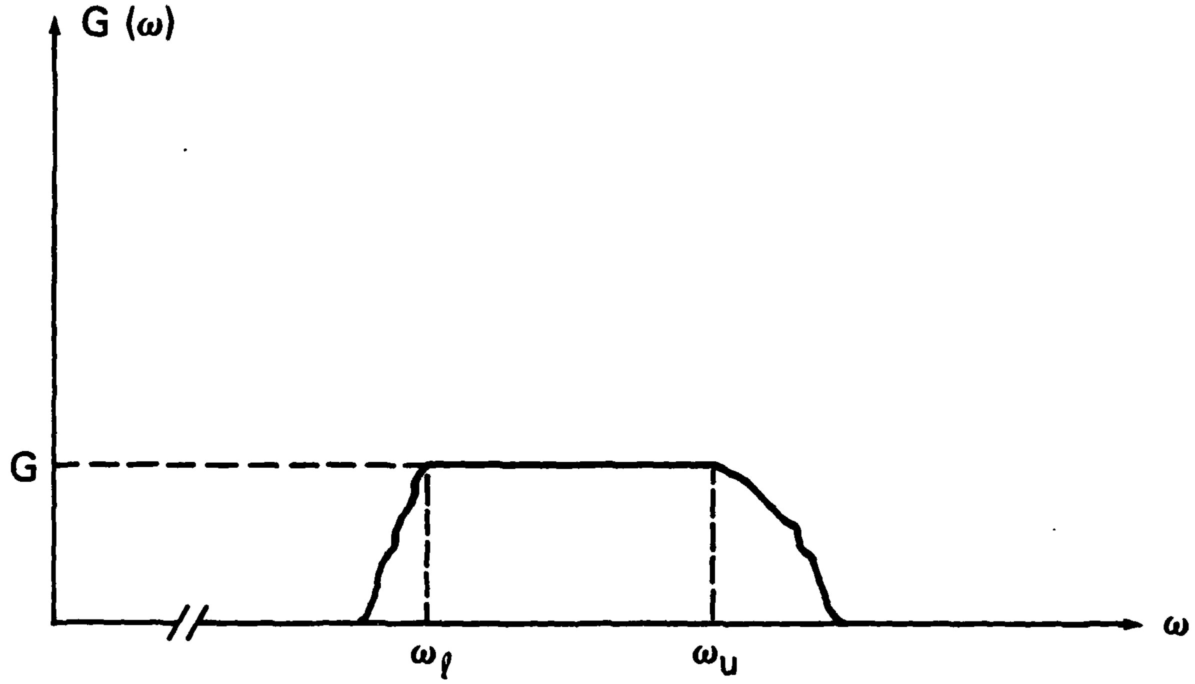

Fig. 5 — The total linear gain $G(\omega)$ as a function of ω.

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